Study on Rotational Speed Feedback Torque Control for Wind Turbine Generator System

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Abstract*—In partial load torque control for variable speed wind turbine generators(VSWTG) rotational speed, which will be feedback signal, is very important parameter. The mathematical model of wind turbine and control regulation for maximizing energy conversion yield has been introduced in this paper. The control system stability and dynamic response are analyzed when using the wind turbine rotor side rotational speed (RSRS) and the generator side rotational speed(GSRS) as feedback signal in torque control respectively ,and the effect the drive train damping and wind speed on system stability are investigated simultaneously. Analysis- and simulation results show that, when using RSRS the stability of wind turbine control system depends on the damping of drive train and the coming wind speed strongly, while the system will be always stable in partial load torque control when using GSRS although wind speed and damping have some effect on the wind turbine system stability. Two real wind turbines of 1.5MW double fed asynchronous generator(DFIAG) are simultaneouly tested with different feedback rotational speed respectively. Test results show that, when using RSRS the generator rotational speed will fluctuate strongly with severe torsion vibrations in higher wind speed, while the wind turbine operate normally for GSRS feedback, which make a very good agreement with analysis- and simulation results.

***Keywords-** torque control, rotational speed, damping, eigenvalues ,vibration, wind turbine*

I. INTRODUCTION

The wind turbine operation area for variable speed wind turbine can be divided into several zones[1,2, 3]. Depending on wind speed acting on blades, Energy conversion objectives and control objectives are different for each zone.

For Middle wind speed zone, the main objective is to maximize the system energy conversion yield. In this partial load zone, the system has to operate at the optimum power coefficient, Pitch angle is then maintained constant at optimum position and rotational speed is controlled to operate at designed blade tip speed ratio, by acting only on the electromagnetic generator torque *Tg*, which is so called torque control.

Rotational speed signal is very important as a feedback signal in wind turbine torque control for variable speed wind turbine generators(VSWTG). Both the wind turbine rotor side rotational speed (RSRS) and the generator side rotational speed(GSRS), one of which will be the control feedback signal, are measured by monitoring and control system. This paper will investigate whether there are some different dynamic responses and stability in wind turbine torque control when using RSRS and GSRS as control feedback signals respectively.

II. WIND TURBINE MODELING AND TORQUE CONTROL STRATEGY

The wind turbine characteristics include aerodynamics, turbine mechanics, generator dynamics, actuator dynamics, as shown in Fig. 1.

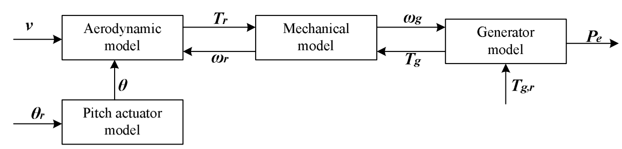

Figure 1. Interconnection of sub-models describing the characteristics of the wind turbine

A. Mechanics[1,4]

The turbine is split into two parts separated by the transmission: rotor side and generator side (Fig.2). The inertia on the rotor side J_r and generator side J_g are illustrated by the leftmost and the rightmost disc respectively. The dynamic nature of the shaft (the drive train dynamics) is illustrated by the damping D_s and the spring constant K_s. The gear ratio N_g is illustrated by the discs in the middle. On the left the model is exited by the rotor torque T_r and on the right the generator torque T_g. The torques T_{sr} and T_{sg} are the torques at each side of the transmission, which are related by the gear ratio:

$$N_g = T_{sr} / T_{sg} \tag{1}$$

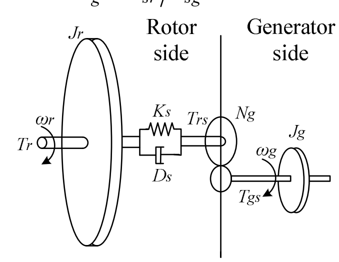

Figure 2. Mechanics structure for variable speed wind turbine with gearbox

The equations describing the dynamics are obtained using Newton's second law for rotating bodies. The results in two equations: one for the rotor side and one for the generator side.

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$$\dot{\omega}_r J_r = T_r - T_{sr} \tag{2}$$

$$\dot{\omega}_g J_g = T_{sg} - T_g \tag{3}$$

Introducing a variable δ [rad] describing the twist of the shaft, leads to the following equation describing the twist of the flexible shaft:

$$T_{sr} = D_s\dot{\delta} + K_s\delta \tag{4}$$

$$\dot{\delta} = \omega_r - \omega_g / N_g \tag{5}$$

B. Aerodynamics

The aerodynamic torque T_r is: $T_r = P_r/\omega_r$ (6)

where the power P_r is: $P_r = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\theta)$ (7)

Where ρ is the air density, R the wind turbine radius and v the effective wind speed. C_p is the efficiency coefficient which is a function of the blade pitch angle θ and the tip speed ratio λ.

In torque control in partial load, the pitch angle is kept constant at optimum position, the analytical approximation of the C_p can be taken from:[5,6,7]

$$C_p(\lambda) = 0.5176(\frac{116}{\lambda} - 9.06)e^{-21(\frac{1}{\lambda}-0.035)} + 0.0068\lambda \cdot \tag{8}$$

C. Generator dynamics

Normally, dynamic responce time constant of generator is rather small so that the generator torque can achieve the demanded value quickly. For the analysis of wind turbine torque control in this paper, the dynamics of generator are therefore be neglected.

D. Torque Control in Partial Load

For torque control in partial load, a simple, successful control strategy shows that the generator torque demand Q_g should be set proportional to the square of the measured generator speed ω_g ((9)) or wind turbine speed ω_r((10)) [1,8,9,10,11,12] in order to achieve peak $C_{p,max}$, where R is the rotor radius, ρ is the air density and N_g is the gearbox ratio, K represents the proportional constant.

$$Q_g = \frac{1}{2}\rho\pi\frac{\omega_g{}^2 R^5}{\lambda_{opt}{}^3 N_g{}^3}C_{p,\max} = K\omega_g{}^2 \tag{9}$$

$$Q_g = \frac{1}{2}\rho\pi\frac{\omega_r{}^2 R^5}{\lambda_{opt}{}^3 N_g}C_{p,\max} = K\omega_r{}^2 N_g{}^2 \tag{10}$$

E. Nonlinear state space description

Combining all the previous equations results in the following set of coupled first order differential equations (state-space model),for RSRS feedback:

$$\dot{\omega}_r = \frac{P_r(\omega_r,v)}{\omega_r J_r} - \frac{\omega_r D_s}{J_r} + \frac{\omega_g D_s}{J_r N_g} - \frac{\delta K_s}{J_r} \tag{11}$$

$$\dot{\omega}_g = \frac{\omega_r D_s}{N_g J_g} - \frac{\omega_g D_s}{N_g{}^2 J_g} + \frac{\delta K_s}{N_g J_g} - \frac{K N_g{}^2 \omega_r{}^2}{J_g} \tag{12}$$

$$\dot{\delta} = \omega_r - \omega_g / N_g \tag{13}$$

Where J_r and J_g are wind turbine rotor inertia and generator inertia especially.

For GSRS feedback (12) has been changed as:

$$\dot{\omega}_g = \frac{\omega_r D_s}{N_g J_g} - \frac{\omega_g D_s}{N_g{}^2 J_g} + \frac{\delta K_s}{N_g J_g} - \frac{K\omega_g{}^2}{J_g} \tag{14}$$

Defining the state and input vector as:

x=[ω_r ω_g δ] $\dot{x} = f(x)$

III. SIMULATION

A. Torque control stability analysis

The linear state space description is trivially obtained by calculating the Jacobians of the system in the point of linearization x^*. The following notation:

$$\bar{x} = x - x^* \tag{15}$$

will be used to describe the deviation of the state from the point of linearization. The linear state space equation is:

$$\dot{\bar{x}} = A\bar{x} = \begin{bmatrix} A_{11} & \frac{D_s}{J_r N_g} & -\frac{K_s}{J_r} \\ A_{12} & A_{22} & \frac{K_s}{J_g N_g} \\ 1 & -1/N_g & 0 \end{bmatrix}_{x=x^*} \begin{bmatrix} \bar{\omega}_r \\ \bar{\omega}_g \\ \bar{\delta} \end{bmatrix} \tag{16}$$

Where, for RSRS feedback control,

$$A_{11} = \frac{\frac{\partial}{\partial\omega_r}P_r(\omega_r,v)}{\omega_r J_r} - \frac{P_r}{\omega_r{}^2 J_r} - \frac{D_s}{J_r}$$

$$A_{12} = \frac{D_s}{J_g N_g} \quad A_{22} = \frac{-D_s}{N_g{}^2 J_g} - \frac{2K\omega_g}{J_g}$$

And for GSRS feed back control,

$$A_{11} = \frac{\frac{\partial}{\partial\omega_r}P_r(\omega_r,v)}{\omega_r J_r} - \frac{P_r}{\omega_r{}^2 J_r} - \frac{D_s}{J_r}$$

$$A_{12} = \frac{D_s}{J_g N_g} - \frac{2KN_g{}^2\omega_r}{J_g} \quad A_{22} = \frac{-D_s}{N_g{}^2 J_g}$$

Due to the complex nonlinear from the aerodynamic force and control method, the analytic solution of the point x^* is difficult to calculate, while the numerical solution for an example is relative easy to be acquired. So in this paper an example of a double fed induction asynchronous generator(DFIAG) has been calculated and simulated, and the basic parameters of this example are: J_r=3.6×10^6kgm^2, J_g=78 kgm^2, N_g=90, R=35m, λ_{opt}=8, $C_{p,opt}$=0.4789, K_s= 1.6×10^8Nm/rad, K=0.1299Nm/rad^2.

When using RSRS and GSRS as control feedback respectively, the local linear stability can be analyzed by calculating the eigenvalues(EVs) of Jacobians according to control theory.

At v=5m/s the equilibrium point is x*=[1.1429 102.8596 0.0008], and the EVs of jacobians with different damping D_s

for GSRS and RSRS are shown in Table(1) and Table(2) respectively. From table(1) and table(2), with the increasing of damping, the real parts of EVs are going smaller, which shows that the smaller the EVs are, the more stable the control system for both GSRS and RSRS feedback control is. Only big damping for RSRS feedback control, i.e. 10^5 Nms/rad at 5m/s in this example, can make the system stable, otherwise some real parts of the EVs are not minus, so that the system is unstable. However the system is always stable for GSRS feedback control, although damping can affect the real part of EVs a little.

TABLE I. EIGENVALUES OF JACOBIANS FOR GSRS FEEDBACK AT DIFFERENT DAMPING IN 5M/S

D_s(Nms/rad)	EV1	EV2	EV3
0	-0.0747	-0.1478+17.2527i	-0.1478-17.2527i
10	-0.0747	-0.1478+17.2527i	-0.1478-17.2527i
10^2	-0.0747	-0.1479+17.2527i	-0.1479-17.2527i
10^3	-0.0747	-0.1487+17.2527i	-0.1487-17.2527i
10^4	-0.0747	-0.1571+17.2526i	-0.1571-17.2526i
10^5	-0.0747	-0.2408+17.2516i	-0.2408-17.2516i

TABLE II. EIGENVALUES OF JACOBIANS FOR RSRS FEEDBACK AT DIFFERENT DAMPING IN 5M/S

D_s(Nms/rad)	EV1	EV2	EV3
0	-0.0747	0.0235+17.2538i	0.0235-17.2538i
10	-0.0747	0.0235+17.2538i	0.0235-17.2538i
10^2	-0.0747	0.0244+17.2538i	0.0244-17.2538i
10^3	-0.0747	0.0226+17.2538i	0.0226-17.2538i
10^4	-0.0747	0.0142+17.2538i	0.0142-17.2538i
10^5	-0.0747	-0.0695+17.2536i	-0.0695-17.2536i

Defining Ds=35000 for this example, and different wind speed are tested. Table(3) illuminate clearly that, with the increasing of wind speed, the system for RSRS feedback goes more unstable, and some EVs of jacobians going from minus to positive indicate system going from stability to instability.

TABLE III. EIGENVALUES OF JACOBIANS AND EQUILIBRIUM POINTS FOR RSRS FEEDBACK AT DAMPING=35000 IN DIFFERENT WIND SPEED

v(m/s)	ω_r*(rad/s)	EV1	EV2	EV3
5	1.1429	-0.0747	-0.0091+17.2538i	-0.0091-17.2538i
6.5	1.4858	-0.0972	-0.002+17.2538i	-0.002-17.2538i
8	1.8286	-0.1196	0.0005+17.2539i	0.0005-17.2539i
10	2.2858	-0.1495	0.0144+17.2541i	0.0144+17.2541i

However, all the EVs real parts of jacobians for system with GSRS feedback go more minus with the increasing wind speed, which can be seen in Table (4).

TABLE IV. EIGENVALUES OF JACOBIANS AND EQUILIBRIUM POINTS FOR GSRS FEEDBACK AT DAMPING=35000 IN DIFFERENT WIND SPEED

v(m/s)	ω_r*(rad/s)	EV1	EV2	EV3
5	1.1429	-0.0747	-0.1804+17.2524i	-0.1804-17.2524i
6.5	1.4858	-0.0972	-0.2247+17.2516i	-0.2247-17.2516i
8	1.8286	-0.1196	-0.269+17.2506i	-0.269-17.2506i
10	2.2858	-0.1495	-0.3281+17.2491i	-0.3281-17.2491i

B. *Simulation analysis*

A simulation has been done, in which effective wind speed with turbulence is modeled using Wind Turbine Blockset of Aalborg University[13] and the aerodynamic model, drive train model and torque control model are designed according the methods discussed above. Fig.3 shows the system response for GSRS feedback in wind speed 8m/s and damping 5000 Nms/rad, which illustrate the normal operation of wind turbine. With the same simulation parameters, the system with RSRS feedback becomes unstable, i.e. the rotational speed and power fluctuate strongly, as shown in Fig.4.

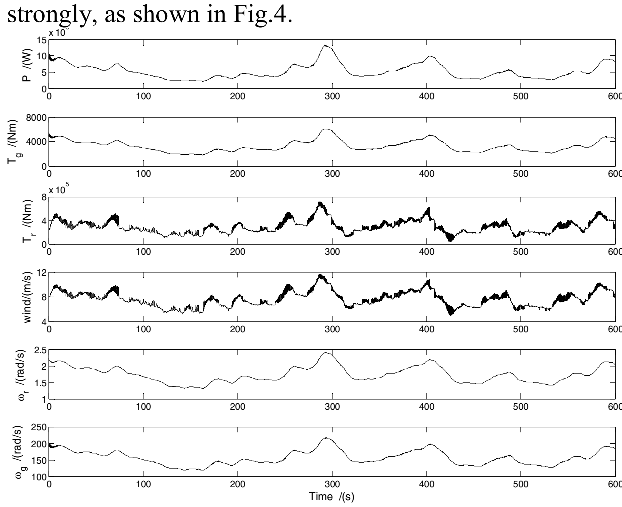

Figure 3. Simulation results GSRS feedback control at wind speed 8m/s

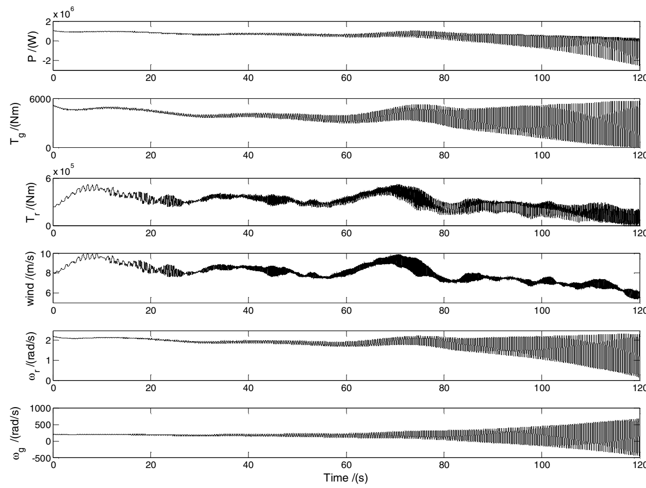

Figure 4. Simulation results RSRS feedback control at wind speed 8m/s

IV. A REAL WIND TURBINE TEST

According to the analysis results above, real 1.5MW DFIAG wind turbines in Hebei China have been tested. Test results show that, when wind speed is higher than a certain value, i.e. about 8m/s for this test , using RSRS as feedback signal of torque control, the wind turbine drive train will

vibrate strongly and rotational speed, especially generator side rotational speed, fluctuate strongly. However, below this certain wind speed the wind turbine can operate normally, because drive train damping plays a main role in small wind, which makes a good agreement with the simulation analysis results above. When using generator side rotational speed as feed back signal of torque control, the wind turbine can operate normally at any wind speed. Fig. 5 have shown the generator rotational comparison results for RSRS and GSRS feedback respectively at two real wind turbines in higher wind speed. Fig. 6 shows the comparison results of torsional vibrations for RSRS at low and higher wind speed.

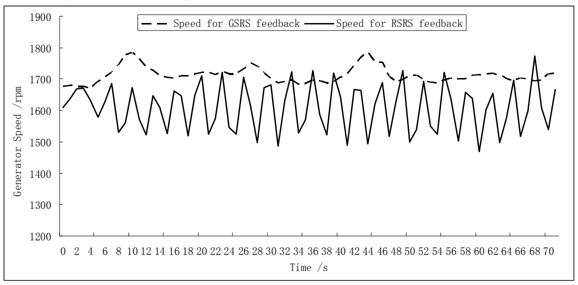

Figure 5. Simultaneous test results of rotational speed for 2 real wind turbines using RSRS and GSRS feedback control respectively

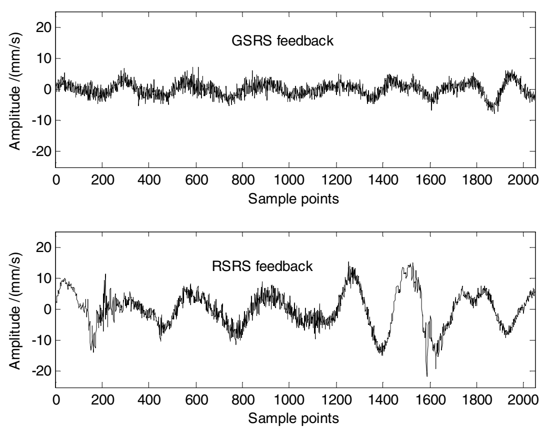

Figure 6. Simultaneous test results of shaft vibrations for 2 real wind turbines using RSRS and GSRS feedback control respectively

V. CONCLUSIONS

In this paper wind turbine models and torque control regulation for VSWTG have been presented. State space equations model combined with torque control regulation and its linearization equation at equilibrium point have been improved. Thus, the stability of wind turbine system in torque control when using RSRS and GSRS as control feedback signals respectively can be analyzed.

The eigenvalues of jacobians for linear system are calculated at different dampings and wind speeds, so that the system local stability can be judged. The analysis results indicate following conclusions. The wind turbine system with RSRS feedback control can be stable only at high damping, and it will be more unstable with increasing wind speed. However, the wind turbine system with GSRS feedback control will be always stable at any damping and wind speed and increasing wind speed can make the system more stable, which is opposite with RSRS feedback. For both GSRS- and RSRS feedback, increasing damping can make system more stable.

A simulation has been done, in which wind speed took turbulence into account. For RSRS feedback, the rotational speed and power will surge strongly at normal damping. On the contrary the system with GSRS feedback can operate very well in the same simulation environment, which is consistent with the analysis results.

Two real wind turbines of 1.5MW DFIAG are simultaneously tested with different feedback rotational speed respectively. Test results show that, when using RSRS the generator rotational speed will fluctuate strongly with severe torsion vibrations in higher wind speed, while the wind turbine operate normally for GSRS feedback, which make a very good agreement with analysis- and simulation results.

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